Refraction of TM01 radially polarized mode from a chemically etched fiber

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Refraction of TM_{01} radially polarized mode from a chemically etched fiber

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Abstract

We propose a method for producing and controlling a radially polarized beam based on the lateral refraction of the TM_{01} mode from a fiber after chemical etching of the cladding. Two aspects are studied: (1) the quality of the refracted beam as a function of the geometry of the etched segment, (2) the method of polarization control by a series of azimuthal detectors. The polarization is modified by a stress controller classically used with single mode fibers.

1. Introduction

Radially polarized beams have proved their interest both in confocal microscopy [1], in near-field microscopy [2] and in laser machining [3]. Among the different ways of beam shaping, an attractive one is the use of the TM_{01} propagation mode from a two-mode optical fiber [4]. A first difficulty comes from the existence of the fundamental HE_{11} mode whatever be the index profile of the core [5]. Several method has been proposed for selective launching of LP_{11} mode since the 80's, based on phase masks [6,7]. To avoid any residual coupling on the HE_{11} mode, the most reliable method of mode filtering at the fiber output is lateral refraction from the fiber after chemical etching of the cladding [8,9]. The object of this paper is to study in more details the optical quality of the circular refracted beam that can be expected after the proper chemical etching of a fiber: cross-talk with HE_{11} mode and polarisation control.

The second difficulty consists in the degeneracy of LP_{11} mode, or the coupling between HE_{21}, TM_{01} and TE_{01} modes. It has been proved that the injection of LP_{11} mode can be compensated by a proper stress generation on the fiber [4]. We propose a polarization control by a series of azimuthal detectors.

2. Modal properties of an etched fiber

The lateral refraction of any guided mode of an optical fiber can be obtained by transforming the weakly guiding fiber into a leaky waveguide. This is easily done by a chemical etching of the optical cladding in a buffered HF solution and immersion of the etched fiber in a high index liquid. The maximum etching speed is about 1 micron/minute in 40% HF and can be reduced in diluted acid to improve the precision on the final diameter. The etched segment (filament) of the fiber can be modelled by a 3-medium (double-cladding) waveguide connected to the original fiber by a tapered transition (Fig.1).

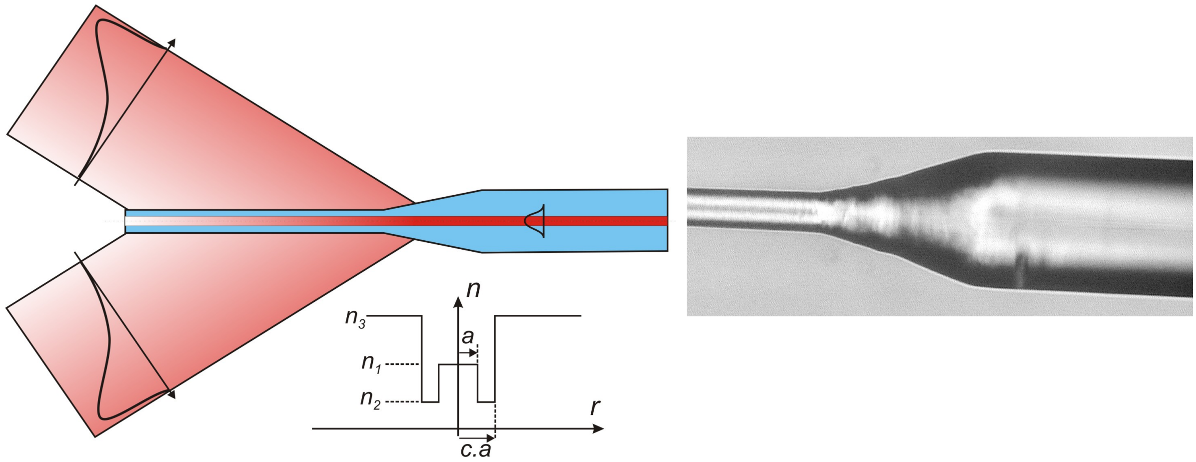

Fig.1 – Principle of the lateral refraction of guided modes.

The leakage rate of this device depends on the residual thickness of the cladding. The beam profile depends on the filament length and the taper shape. In a first step we consider the index profile of Fig.1 and calculate the parameters of the leaky mode as a function of the cladding thickness. The dispersion curve u(V) has been studied by [10] in the case of guided modes (n3<n1). We use the same formula in the case n3>n1 where all modes become refracted in the high index medium:

$$\frac{J_n(u)}{uJ_{n+1}(u)} - \frac{K_n(w)}{wK_{n+1}(w)} = -\left(\frac{J_n(u)}{uJ_{n+1}(u)} + \frac{I_n(w)}{wI_{n+1}(w)}\right)\frac{K_{n+1}(cw)I_{n+1}(w)}{K_{n+1}(w)I_{n+1}(cw)}\,\frac{\frac{K_n(cw)}{cwK_{n+1}(cw)} - \frac{H_n(cW)}{cWH_{n+1}(cW)}}{\frac{I_n(cw)}{cwI_{n+1}(cw)} - \frac{H_n(cW)}{cWH_{n+1}(cW)}}$$

where we write for conciseness :

$$H_n(cW) = H_n^{(1)}(cW) = K_n(icW)$$

and where

- V is the normalized frequency of the reference single cladding fiber :
- $V^2 = (n_1^2-n_2^2)(k_0a)^2$
- u, w, W are the normalized transverse propagation constants in the core, cladding and immersion liquid
- $u^2 + w^2 = V^2$, $u^2 + W^2 = V^2\,(n_1^2-n_3^2)/(n_1^2-n_2^2)$

The attenuation coefficient α of the propagating intensity can be derived from the dispersion curves $u(V)$ by the formulas:

$$\beta^2 = [(n_1k_0)^2-(u/a)^2]^{1/2} \quad , \quad \alpha = im(\beta)$$

The angular width of the refracted modes is related by the diffraction laws to the fiber length along which the mode is emitted. We can reasonably define this emission length as the etched segment itself if the attenuation is weak, or in the opposite case as the propagation distance which gives to the leaky mode a *10 dB* attenuation. The variation of this attenuation length versus the residual cladding thickness is shown on Fig.2 for realistic parameters of the fiber:

$L_a = - \log((0.1)^{1/2}) / \alpha$

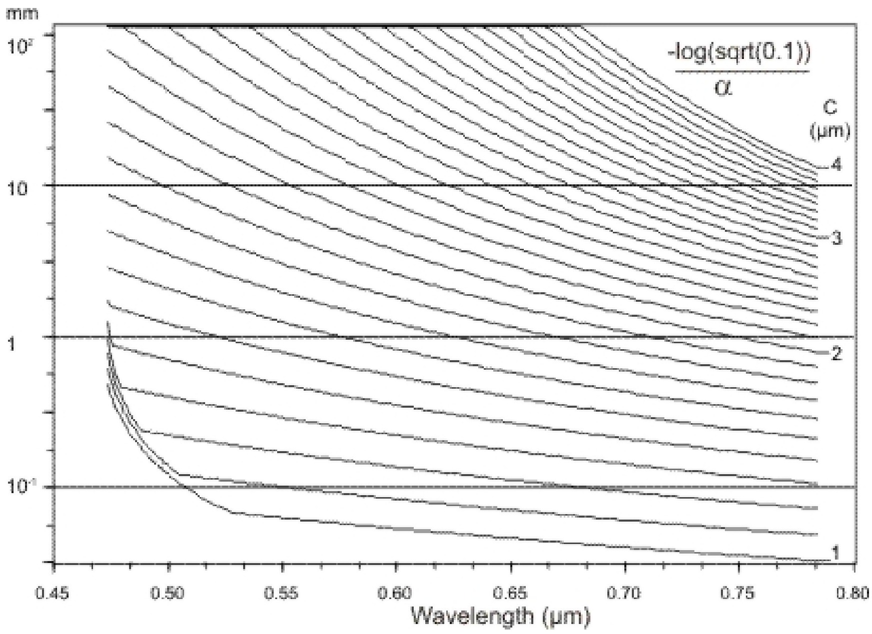

Fig.2 - 10 dB attenuation length for different cladding thickness with a = 2.5 µm, n_1=1.46, Δn=0.005

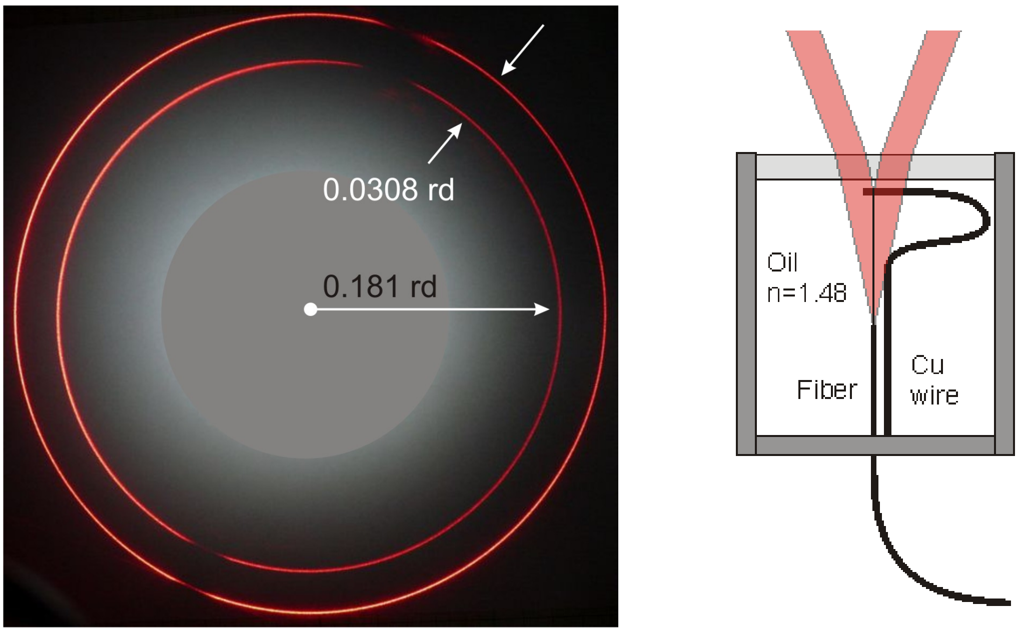

Fig.3 – Refracted beams from the LP_{01} (inner circle) and LP_{11} modes (outer circle).

Two conclusions can be drawn from these curves :

- an important variation of the attenuation in the visible range: for $c = 2$ (diameter of the residual cladding = 2 times the core diameter) L_a rises from *0.8 mm* to *40 mm* between $\lambda = 0.78$ *and* $0.48\ \mu m$,

- the role of the core centering in the fiber section.

The last problem is confirmed by the aspect of the refracted beams visible on Fig.3, that shows the refracted beams from an oil tank where the fiber is immersed. It is maintainded in tension by a spring made of a copper wire. The two circular beams correspond to the modes LP_{01} and LP_{11} (HE_{21} ,TM_{01} ,TE_{01}): both have inhomogeneous azimuthal intensities.

3. Polarisation control

The outer circle of Fig.3 corresponds generally to an arbitrary combination of HE_{21}, TM_{01} and TE_{01} modes. The TM_{01} and TE_{01} modes can be considered as equivalent as far as a couple of $\lambda/2$ birefringent plates can globally rotate the polarisation state in a simple way. A perturbation approach shows how the usual birefringence induced by curvature under tension can couple HE_{21} to TM_{01} or TE_{01} . The correct coupling can be obtained by coiling th fiber on a piezo tube and changing the mechanical tension by the diametral dilatation of the tube. The first step of this work was the fabrication of an *azimuthal polarisation sensor* made of a series of 16 azimuthal detectors (Fig.4c), each of them beeing covered by a polariser radially oriented (not present on the figure).

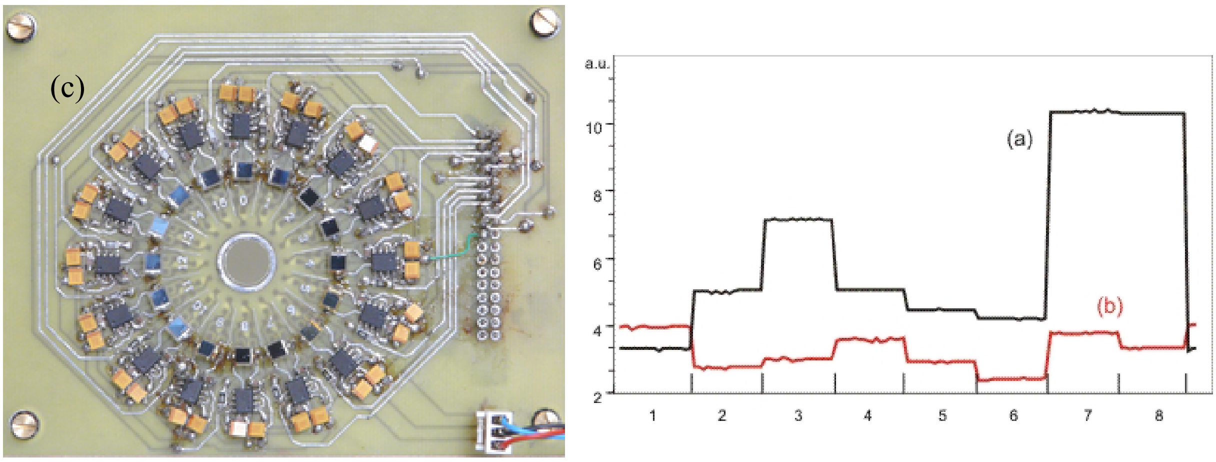

Fig.4 – Azimuthal polarisation sensor. (a) and (b): intensity detected by 8 of the detectors for two different adjustments of the stress controller.

The two different signals of Fig.4a and b are obtained by adjustment of a classical polarisation controller, after calibration of each detector. Although it is not the mored adapted device, the better uniformity of (b) corresponds to a beam which is almost radially polarised.

4. Conclusion

Lateral refraction of TM_{01} mode seems an easy way to obtain a perfect circular beam with azimuthal polarisation usable in near field microscopy. The polarisation control have been carried out by series of azimuthal detectors. A further article will study more systematically the influence of different mechanical stress on the mode coupling hence on the polarization state. The further step consists in testing the profile of the focused beam for the different adjustments of the polarisation. The dissymmetry in the intensity of the refracted beam must be avoided by improving the chemical process and/or chosing the best fiber.

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